EIC (eRHIC) Discussions

Nu Xu[1,2]

Outline:

1) **Introductions:** Emergent QCD properties
2) **Electron Ion Collider**
    - The Science cases
    - Realization and Timeline

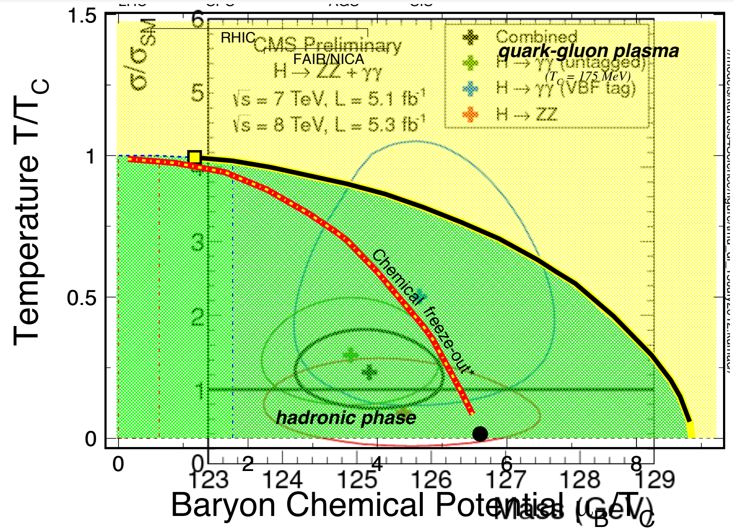
Many thanks to Organizers

[1] College of Physical Science & Technology, Central China Normal University, China
[2] Nuclear Science Division, Lawrence Berkeley National Laboratory, USA

I am not an expert on EIC
I am not a theorist

Many thanks to the advices from
  Haiyan Gao (Duke)
  Jianwei Qiu (BNL)
  Feng Yuan (LBNL)

QCD in the Twenty-First Century



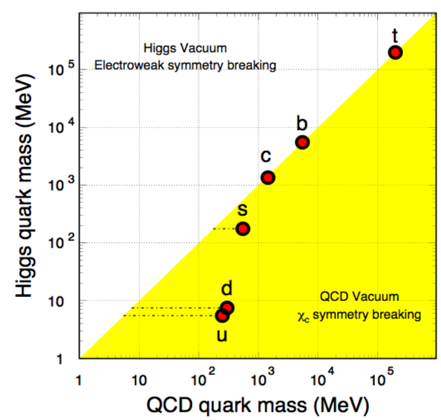
Emergent properties with QCD degrees of freedom!

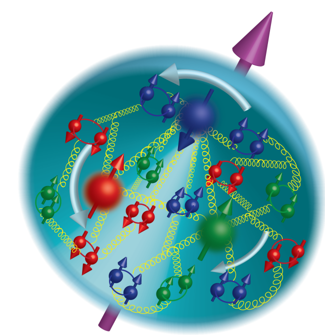
(1) Higgs (-like) Particle –

- **Origin of Mass**, **QCD dof**
- Standard Model ➔ The *Theory*

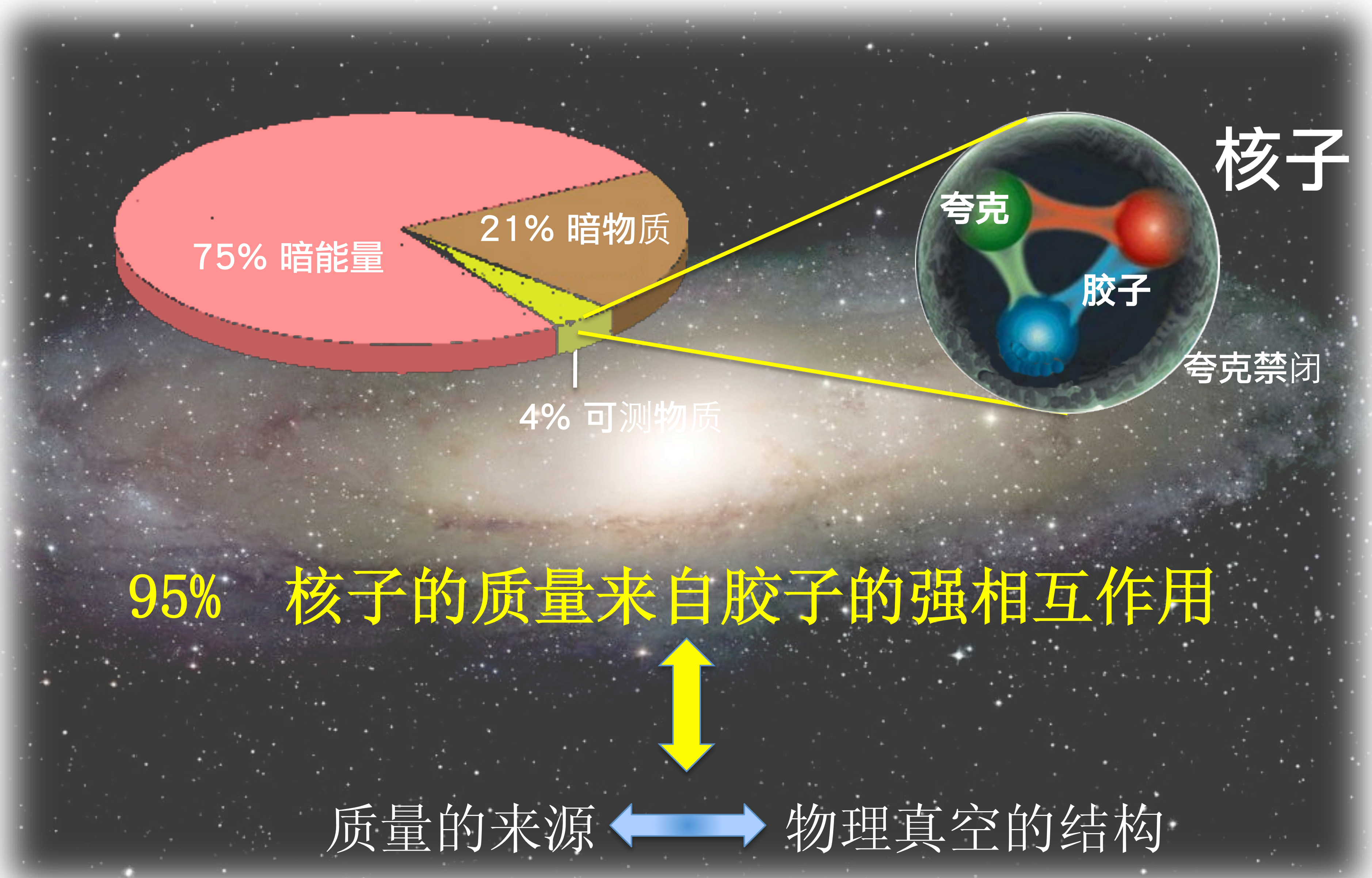
(2) QCD Emerging Properties –

- Confinement, χ_C symmetry
- QCD Phase Structure
- Nucleon helicity structure
- …
- Non-linear QCD at small-x
- …

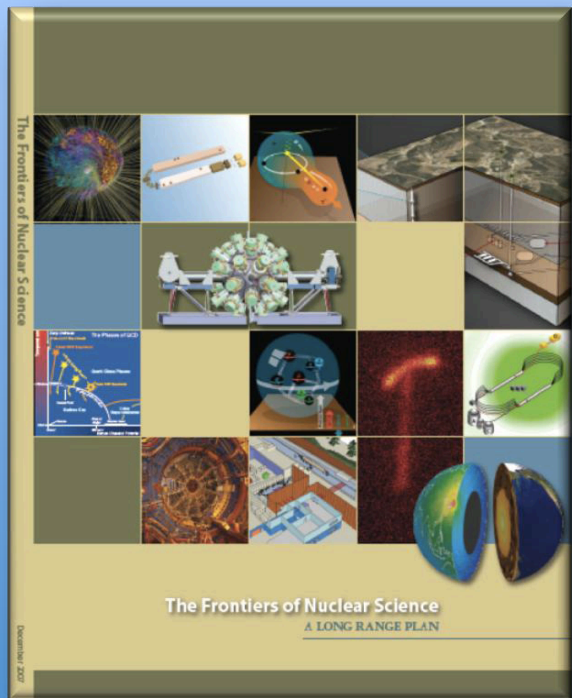




宇宙中物质的组成


75% 暗能量
21% 暗物质
4% 可测物质
核子
夸克
胶子
夸克禁闭
95%　核子的质量来自胶子的强相互作用
质量的来源
物理真空的结构

Science Case for EIC



NSAC 2007 Long-Range Plan:

"An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

- EIC "Collaboration" – R. Milner (MIT) & A. Deshpande (SBU) contact persons, involves BNL and JLab communities
- EICAC advisory comm. → Montgomery & Aronson (BNL)
- JLab and BNL are both developing "staged" designs
- Next NSAC Long Range Plan, 2013-2014

Science Case for EIC

Fundamental scientific questions:

1) How are the sea quarks and gluons, and their spins distributed in space and momentum inside the nucleon? How are these quark and gluon distributions correlated with overall nucleon properties, such as its spin direction? What is the role of orbital motion of sea quarks and gluons in building the nucleon spin?

2) Where does the saturation of gluon densities set in? Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

3) How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei? How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

- EIC Whitepaper executive summary, 2012

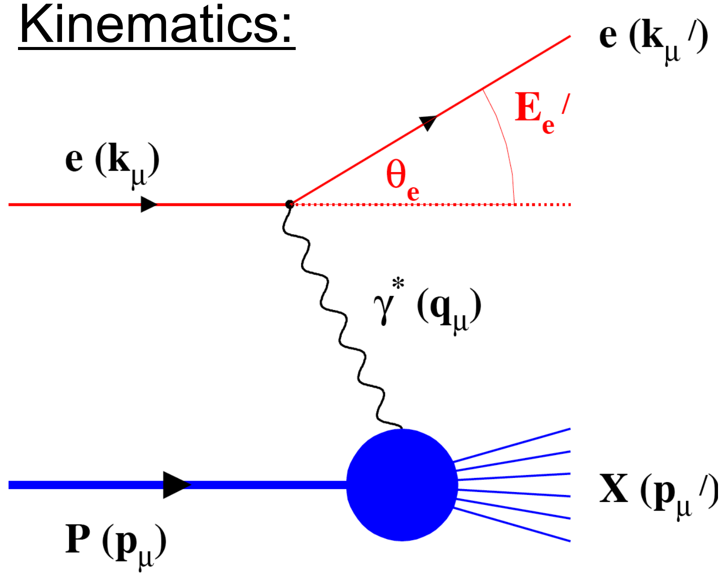
Science Case for EIC

Electron Ion Collider:

1) A collider is needed to provide kinematic reach well into the gluon-dominated regime
2) Electron beams are needed to bring to bear the unmatched precision of the electro-magnetic interaction as a probe
3) Polarized nucleon beams are needed to determine the correlations of sea quark and gluon distributions with the nucleon spin
4) Heavy ion beams are needed to provide precocious access to the regime of saturated gluon densities and offer a precise dial in the study of propagation-length for color charges in nuclear matter.

Deep Inelastic Scattering
Precision + Control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron :

$$z = \frac{E_h}{\nu}; p_t$$

Inclusive events: **e+p/A → e'**+X
Semi-inclusive events: **e+p/A → e'**+h(π,K,p,jet)+X
Exclusive events: **e+p/A → e'**+ p'/A'+ h(π,K,p,jet)

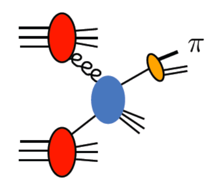
e and e' are precisely determined in experiment
→ Advantage over that of the p+A collisions

QCD and Strong-Interactions

1） QCD is the theory for strong interactions. Its Lagrange is simple (deceivingly simple!):

$$L = \bar{\psi}(i\gamma\cdot\partial - m_q)\psi - \frac{1}{4}F^{\mu\nu a}F_{\mu\nu a} - g_s\bar{\psi}\gamma\cdot A\psi$$

2） Calculating for the scattering process is very complicated (assuming the factorization works)



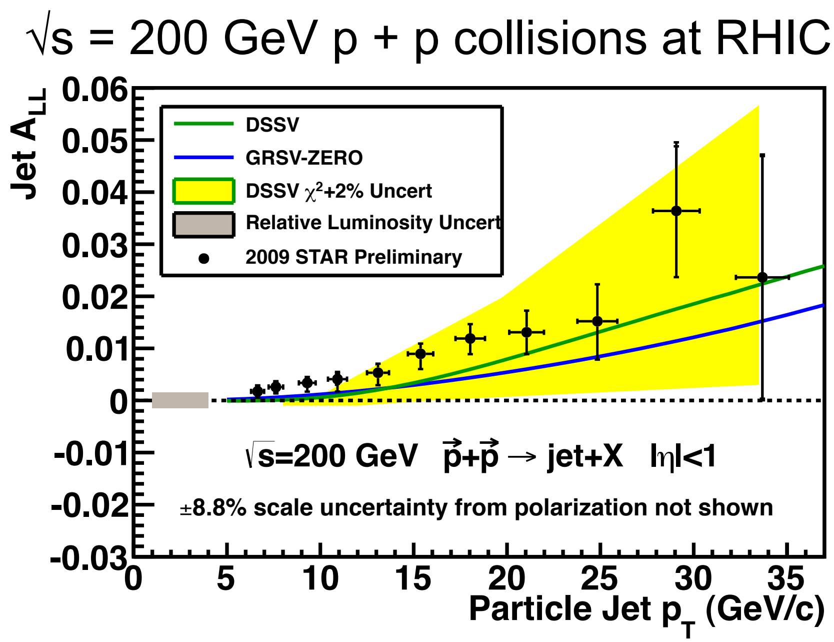
$$\frac{d\sigma}{dp_T d\eta} = \int_{x_a^0}^{1} dx_a \int_{x_b^0}^{1} dx_b \int_{z_c^0}^{1} dz_c \boxed{f_a(x_a)\, f_b(x_b)} \boxed{\frac{d\hat{\sigma}_{ab\to c}}{dp_T d\eta}} \boxed{D_c(z_c)}$$

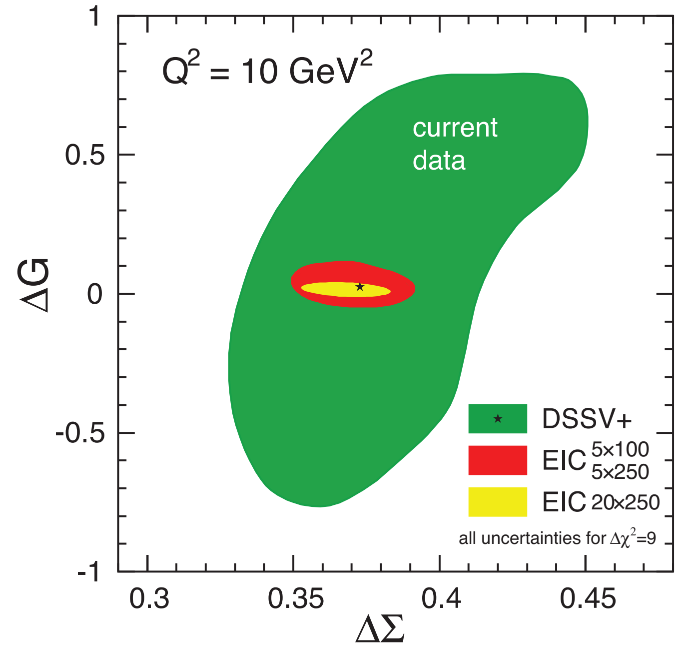
Parton distribution function: NpQCD

pQCD process

Hadronization: NpQCD

g/q Contributions to Proton Spin

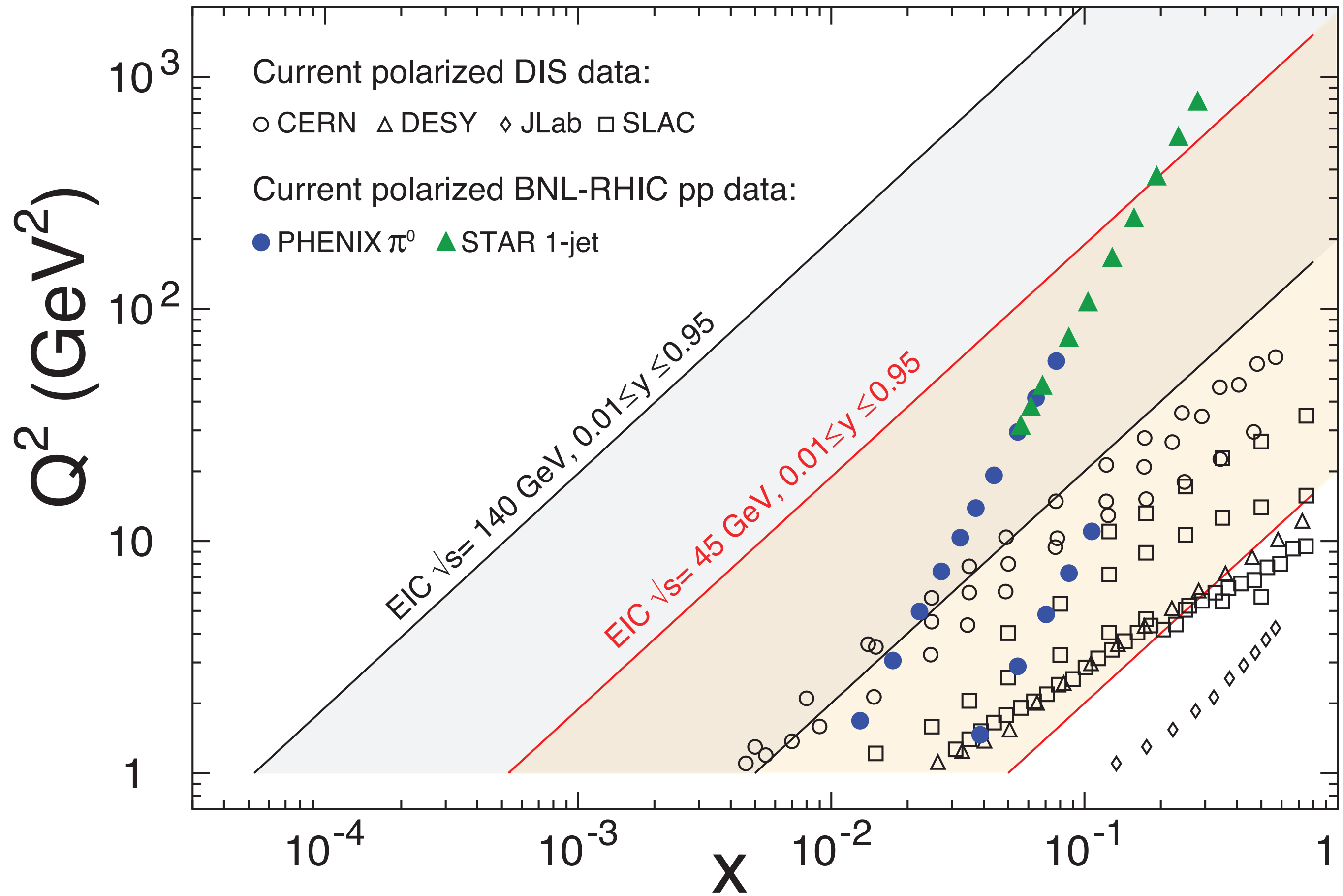




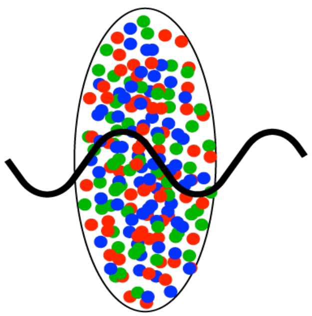
1) Recent analysis of RHIC pp data implies significant contributions to proton spin from gluons, as much as 20% ($0.05 < x_g < 0.2$), with large errors.

2) EIC will provide precision determination of both gluon and quark helicity contributions, ΔG and ΔΣ, respectively, to the proton spin.

EIC Kinematics Coverage (ep)



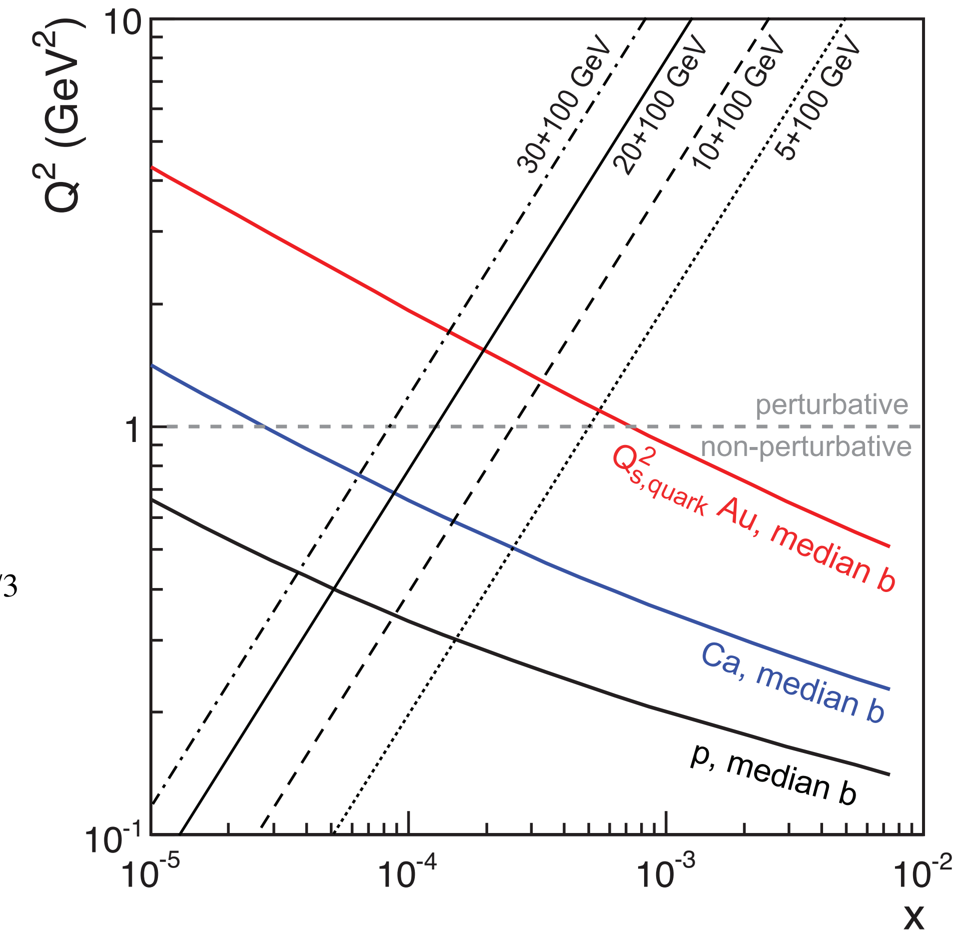
A Magnifiers of Gluon Density?



$L \sim (2m_N x)^{-1} > 2\ R_A \sim A^{1/3}$

Probe interacts all nucleons coherently

$$(Q_s^A)^2 \approx cQ_0^2 \left(\frac{A}{x}\right)^{1/3}$$

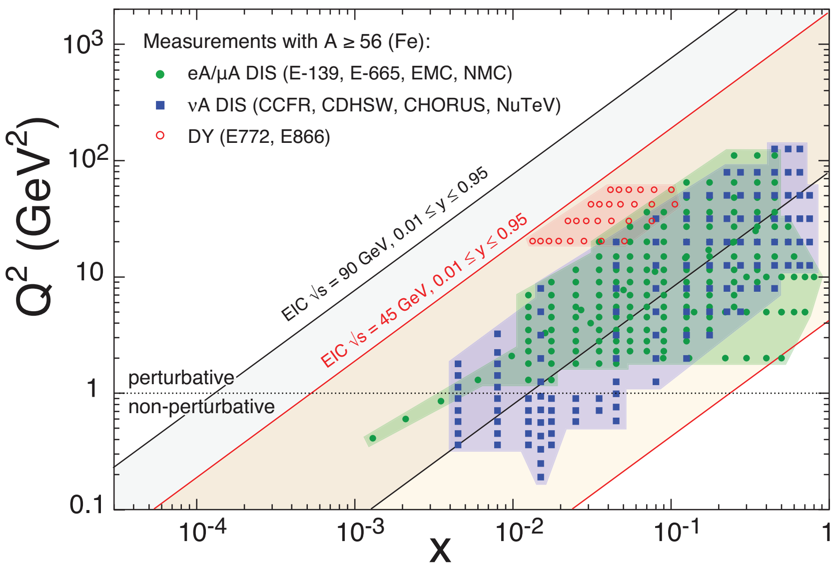


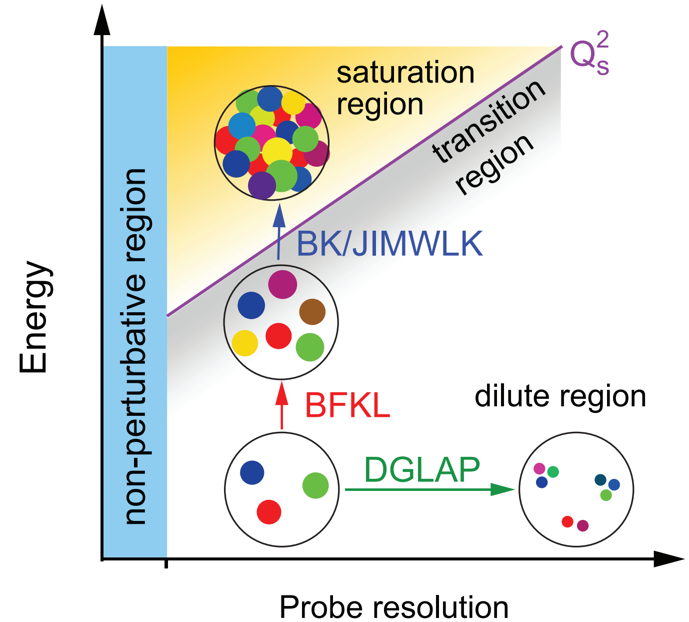
Enhancement of Q_S with A, not just energy!

Kowalski, Teaney, PRD 68:114005

Kowalski, Lappi, Venugopalan, PRL 2008

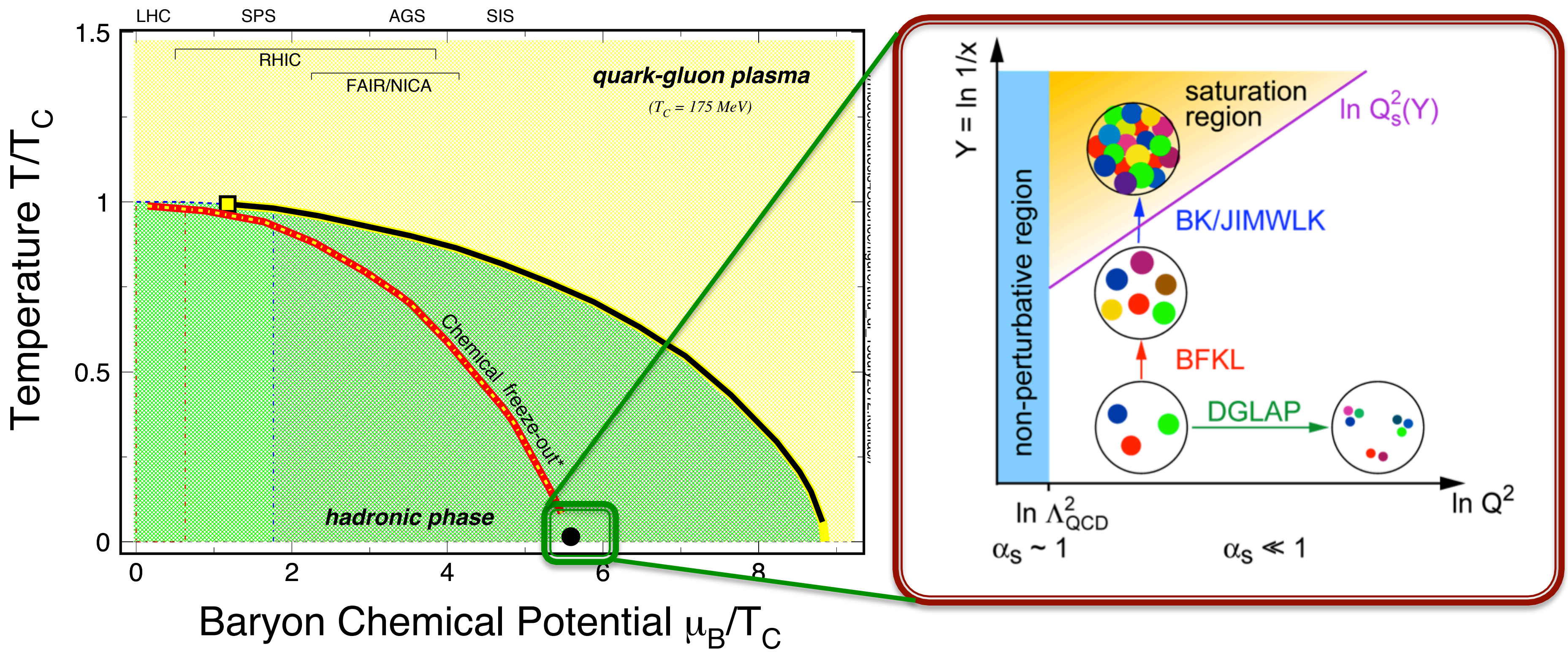
EIC Kinematics Coverage (eA)





QCD Phase Structure

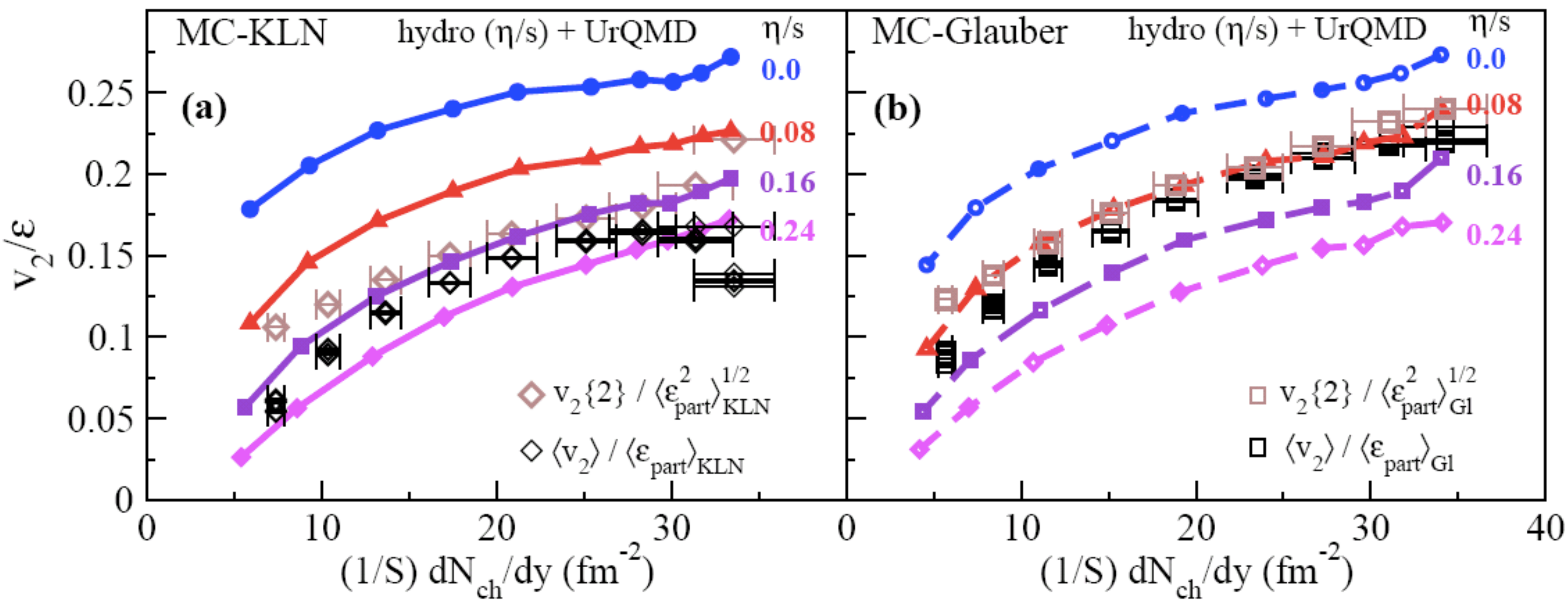
Hot QCD Matter | Cold QCD Matter



RHIC | EIC (eRHIC)

Study phase structure with QCD degrees of freedom

v_2: Hydrodynamic Model vs. Data

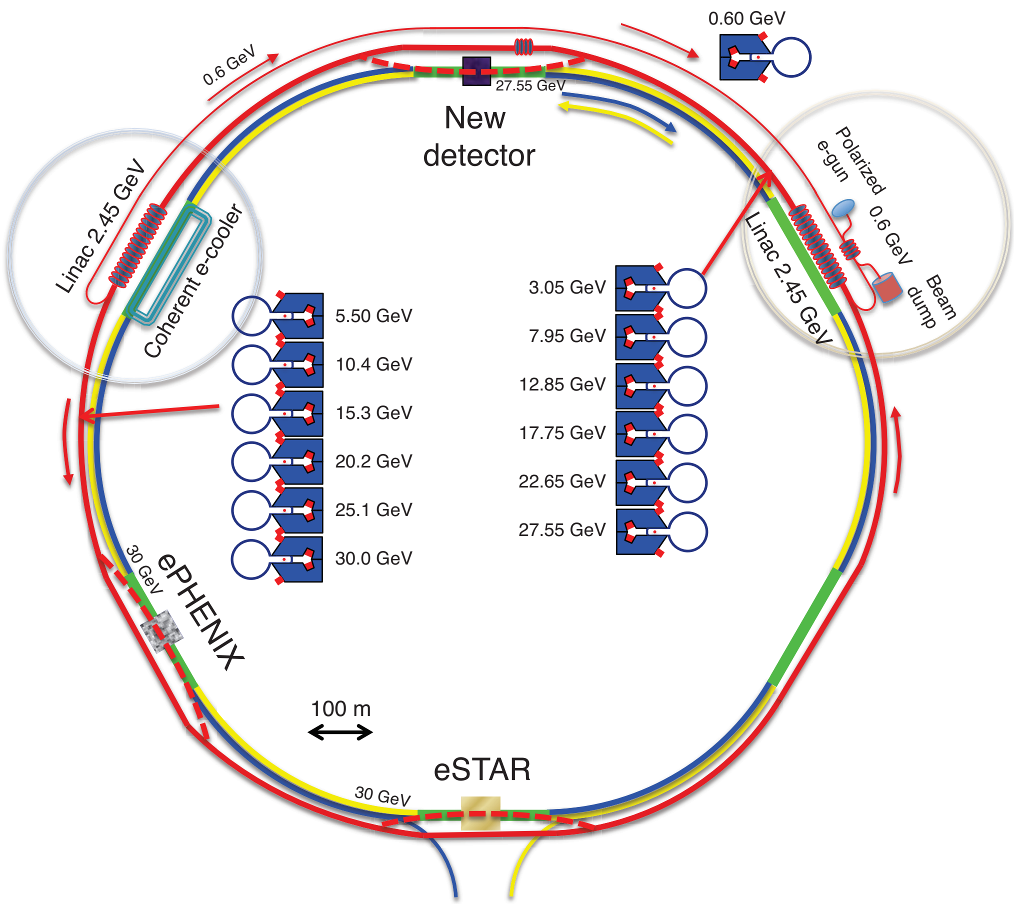


➔ Small value of specific viscosity over entropy ***η/s***

➔ Model uncertainty dominated by initial eccentricity ε

Model: Song *et al. arXiv:1011.2783*

RHIC Version: eRHIC

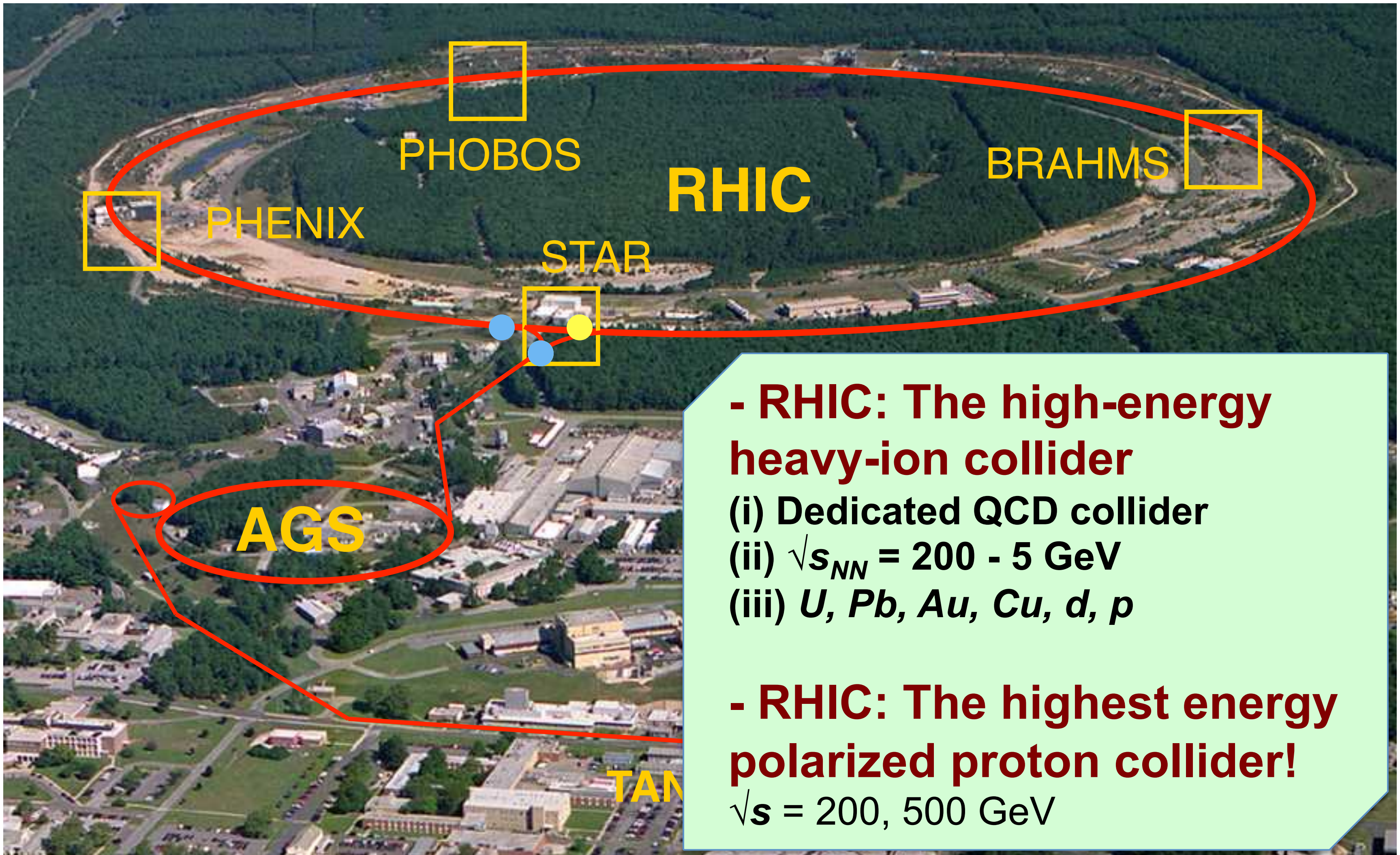


1) Reuses RHIC tunnel & detector halls ⇒ minimal civil constructions
2) Reuses significant fractions of STAR/PHENIX detectors
3) Exploits existing HI beams for precocious access to very high gluon density regime
4) Polarized p and HI beam capabilities already exist (RHIC replacement cost ~$2B)
5) Design allows staging approach, start with 5-10 GeV and upgrade to ~20 GeV polarized **e⁻** beam

➢ Add an electron ring, reuse RHIC ➔ eRHIC

Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



- RHIC: The high-energy heavy-ion collider

(i) Dedicated QCD collider

(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV

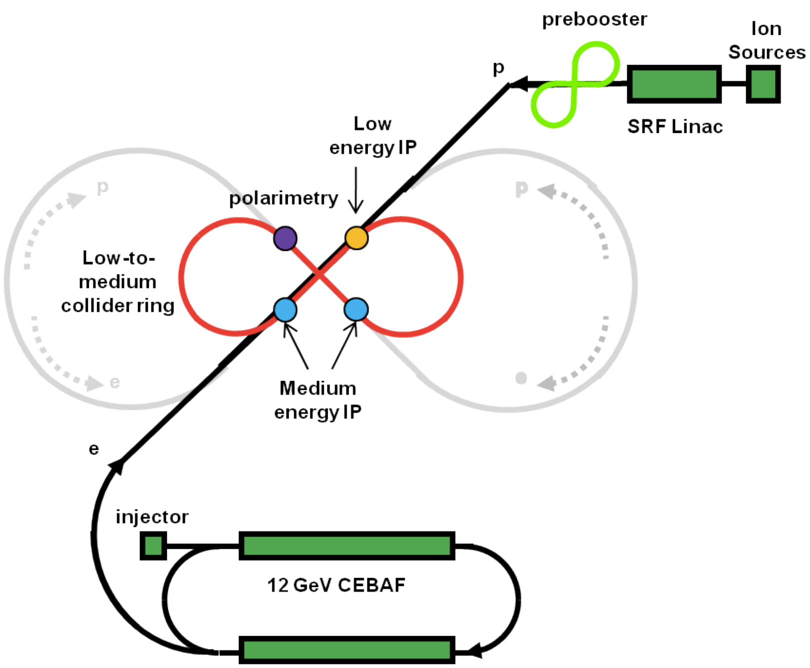
(iii) *U, Pb, Au, Cu, d, p*

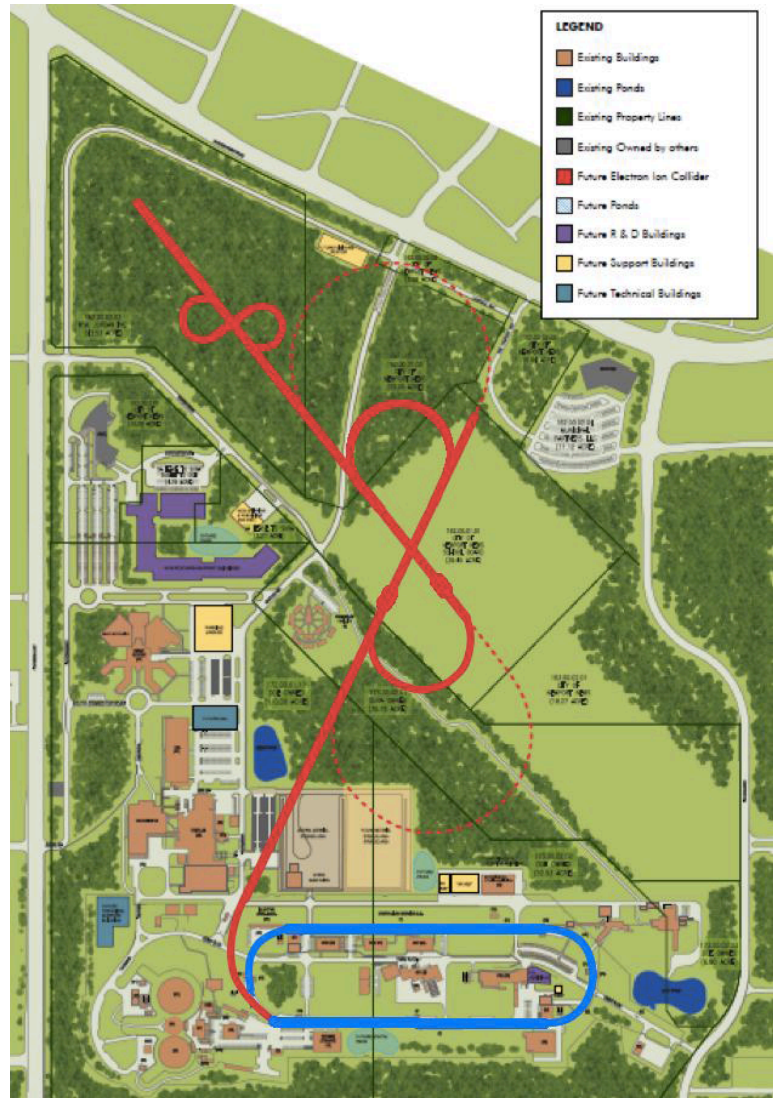
- RHIC: The highest energy polarized proton collider!

$\sqrt{s}$ = 200, 500 GeV

Animation M. Lisa

JLab Version: mEIC/EIC



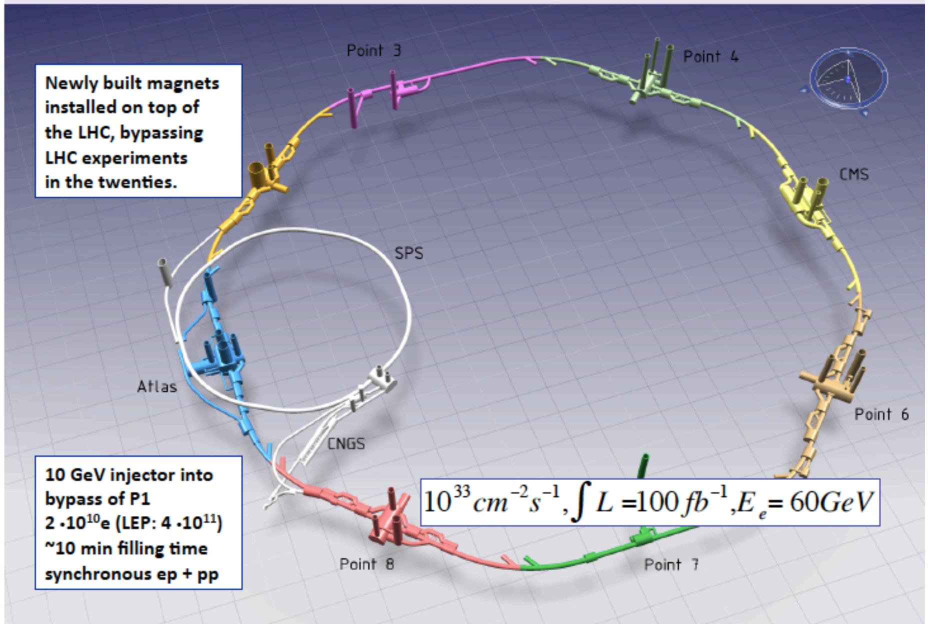


Initial configuration (MEIC):

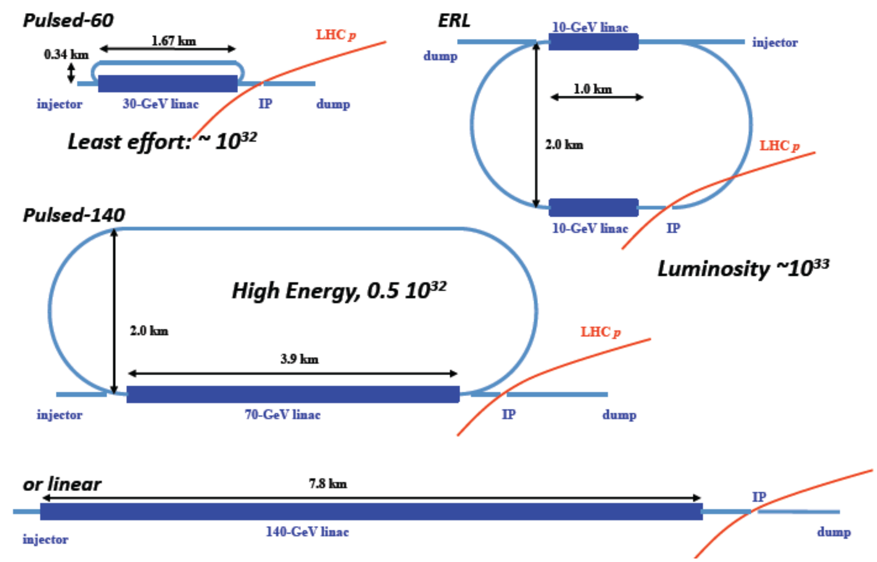
1) 3-11 GeV on 20-100 GeV ep/eA collider
2) fully-polarized, longitudinal and transverse
3) luminosity: up to few x 10^{34} e-p cm^{-2} s^{-1}
4) Upgradable to higher energies (250 GeV protons)

LHeC

Ring-Ring configuration



Linac-Ring Configurations

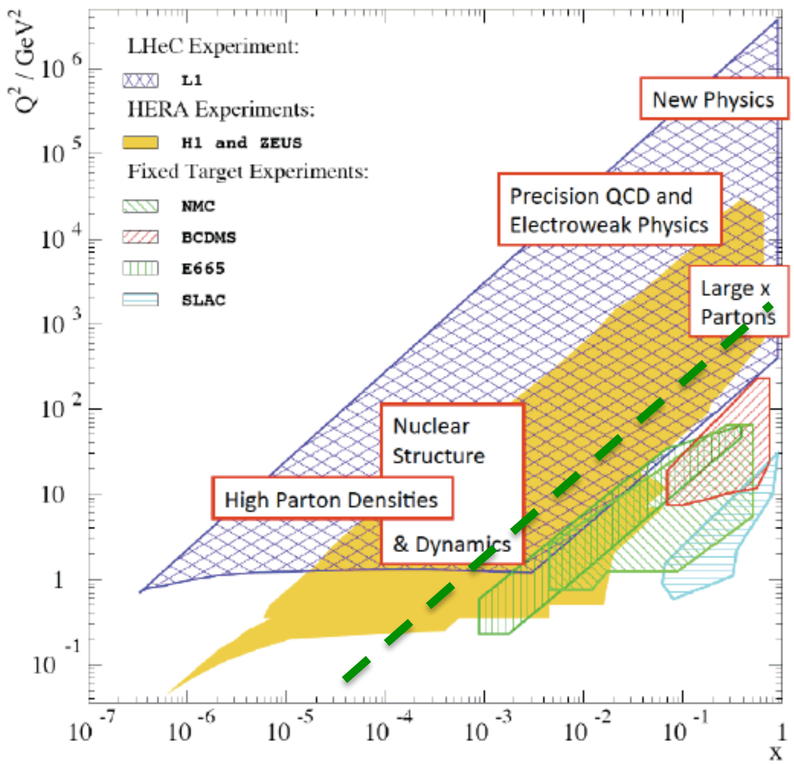


LHeC Physics:

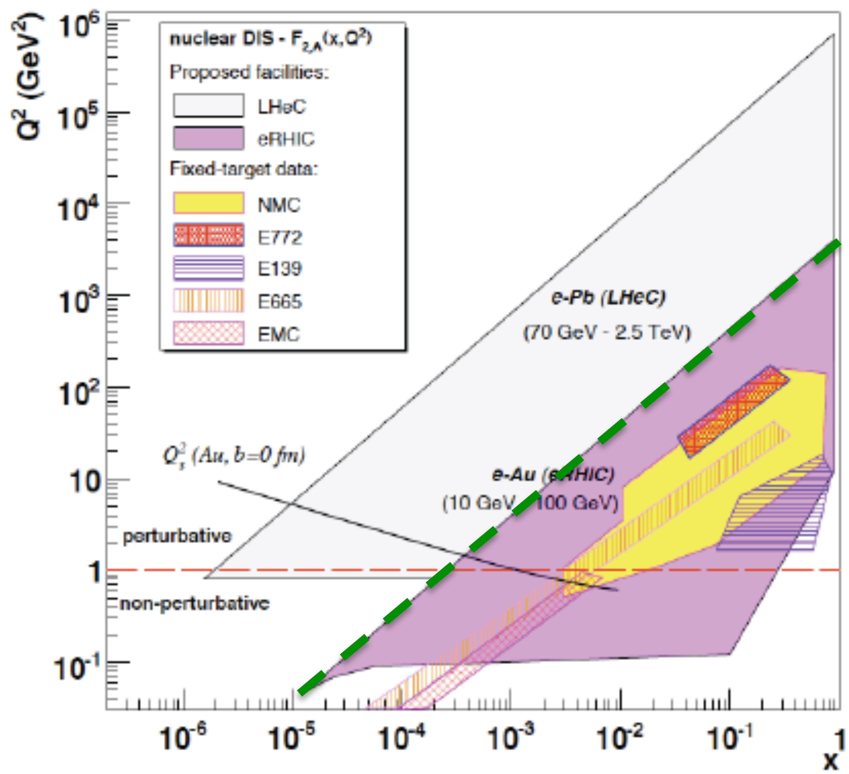
Proton structure & QCD, small-x physics eP & eA

Electron-Quark systems BSM: at 1 TeV scale
Search for new EW physics: RH-W's, Contact Interactions

LHeC

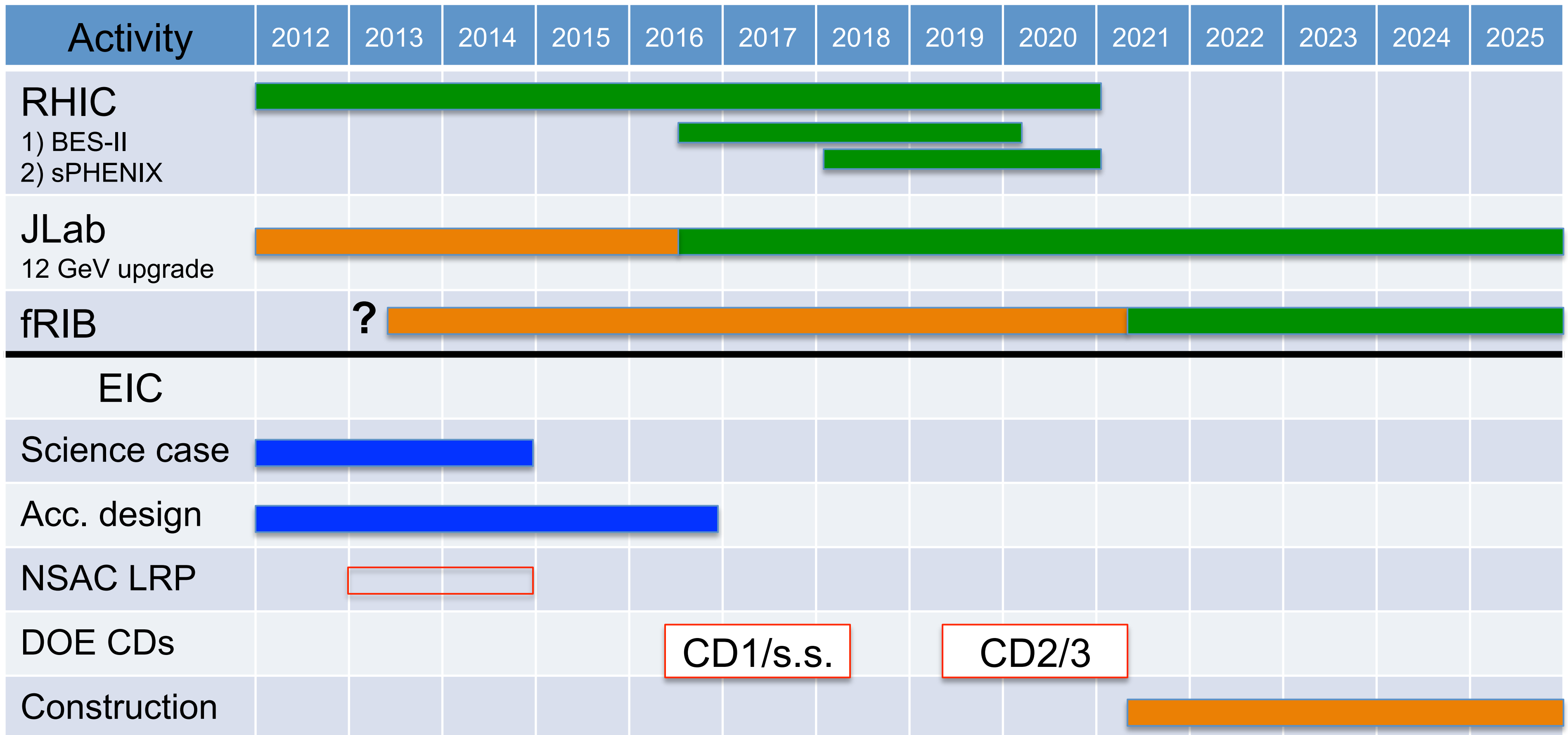


eA → eX



1) Kinematic coverage much wider than that of EIC
2) According to the recent discussions on priorities at LHC, the LHeC project is unlikely to take place before 2025

Envisioned EIC Timeline



Summary

JLab (e scatterings)

- Large-x region QCD phenomena
- Valance quark dominant

RHIC

- HI collisions: hot QCD matter properties, gluons play important role. Initial condition unknown
- Polarized pp collisions: helicity structure at $0.05 < x_g < 0.5$.

EIC

Study Gluon dominant cold QCD matter with unprecedented precision and kinematics reaches

- Gluon/quark space-momentum correlation in nucleon
- Gluon/quark helicity distributions at small-x region
- Dynamical evolution from cold QCD matter to the formation of QGP in HI collisions

EIC Extremes

1) Extreme small-x region, extreme gluon density expected
2) High intensity nucleon, HI, and electron beam accelerations

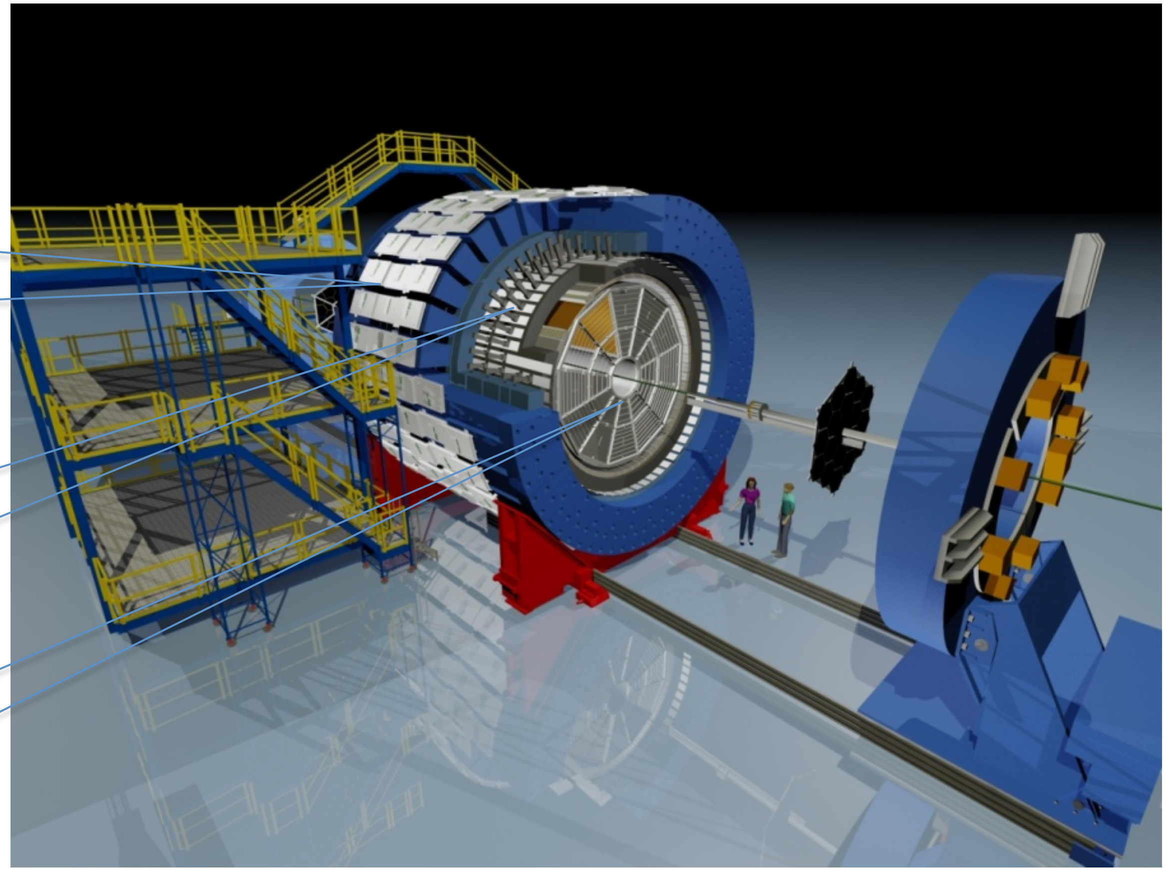
Chinese Contributions to RHIC

Barrel MRPC MTD:
1) ~$2.8M (0.8)
2) 2014

Barrel MRPC TOF:
1) ~$5.4M (1.2)
2) Completed 2010

Si-Pixel HFT:
1) ~$16.5M (1)
2) 2014

HLT: ~ $4M (0.5)



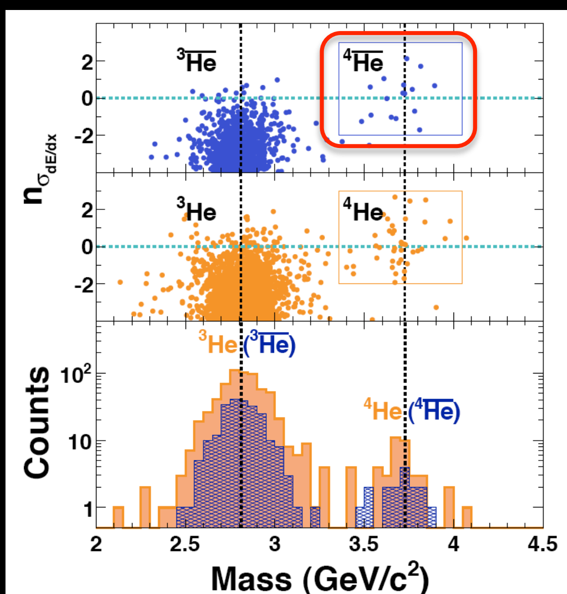
1) Detector operation
2) Data calibration, analysis, publications
3) PWG co-conveners
4) Future upgrades and eRHIC

Antimatter Discoveries at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

by ***STAR Collaboration***
Nature*, 473, 353(2011).*



Science March, 2010

"Observation of an Antimatter Hypernucleus"

by ***STAR Collaboration***
Science*, 328, 58(2010).*